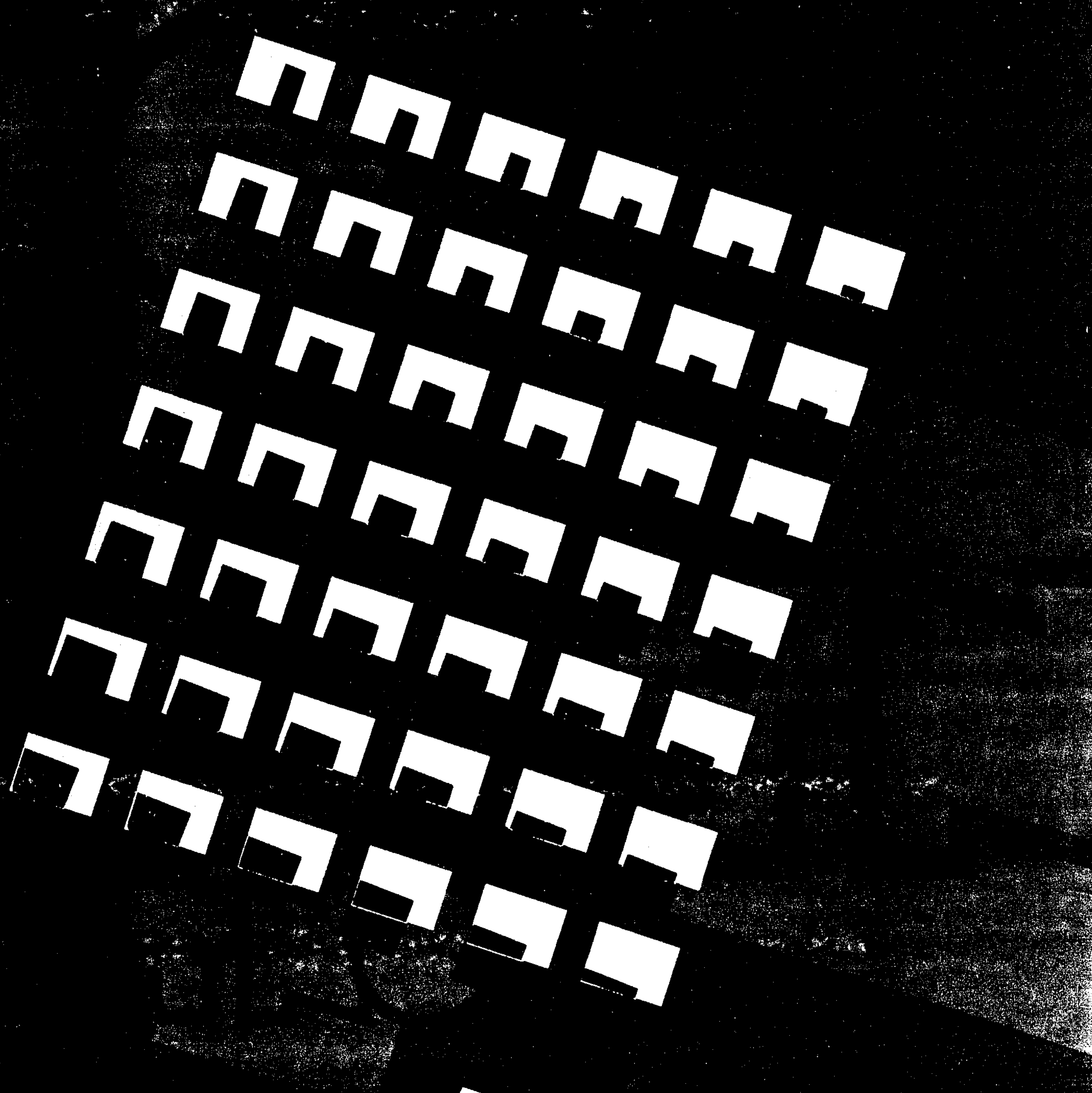
TNO report
FEL-94-A177

Motion Analysis of bird migration

TNO Physics and Electronics
Laboratory



TNO report
FEL-94-A177

Motion Analysis of bird migration

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

TNO Physics and Electronics Laboratory

Oude Waalsdorperweg 63
P.O. Box 96864
2509 JG The Hague
The Netherlands

Phone 070 374 00 00
Fax 070 328 09 61

Date
April 1996

Author(s)
M.W. Ockeloen
J. Nobel

19960801 092

Classification		
Classified by	:	L.S. Buurma
Classification date	:	18 October 1995

Title	:	Ongerubriceerd
Managementuittreksel	:	Ongerubriceerd
Abstract	:	Ongerubriceerd
Report text	:	Ongerubriceerd
Appendix A	:	Ongerubriceerd

Copy no.	:	8	
No. of copies	:	21	
No. of pages	:	26	(incl. appendix, excl. RDP & distribution list)
No. of appendices	:	1	

All information which is classified according to Dutch regulations shall be treated by the recipient in the same way as classified information of corresponding value in his own country. No part of this information will be disclosed to any party.

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

TNO Physics and Electronics Laboratory is part of TNO Defence Research which further consists of:

TNO Prins Maurits Laboratory
TNO Human Factors Research Institute

Netherlands Organization for Applied Scientific Research

Managementuittreksel

Titel	:	Motion Analysis of bird migration
Auteur(s)	:	Drs. M.W. Ockeloen, Ir. J. Nobel
Datum	:	april 1996
Opdrachtnr.	:	A90KLu670
IWP-nr.	:	757.1
Rapportnr.	:	FEL-94-A177

Om vogelaanvaringen tijdens oefenvluchten te voorkomen, is door TNO-FEL voor de KLu het ROBIN systeem ontwikkeld. Het ROBIN systeem werkt op stilstaande radarbeelden. Omdat juist beweging van objecten in het radarbeeld veel informatie geeft omtrent de aard van het object, biedt bewegingsanalyse op een reeks beelden een goede mogelijkheid om filtertechnieken te ontwikkelen die beter zijn dan filtertechnieken op een enkel beeld.
In vervolg op ROBIN is daarom het project "Bewegingsanalyse vogeltrek" opgezet met als doel te komen tot een implementeerbaar filter gebaseerd op bewegingsanalyse.
In het onderzoek wordt een aantal mogelijke methoden van bewegingsanalyse vergeleken. Van de meestbelovende "object matching" methode wordt een algoritme ontwikkeld en een aantal implementatiefacetten belicht. De bevindingen van het onderzoek zijn in dit rapport opgenomen. Verder werd een implementatie gebaseerd op dit onderzoek gerealiseerd en aan de Klu aangeboden.
Een uitgebreide versie ervan is thans bij de Klu in gebruik.

Contents

1 Introduction....4
1.1 Bird migration 4
1.2 The ROBIN system 4
1.3 Objectives of the project "Motion Analysis of Bird Migration" 5
1.4 Digital radar images 5

2 Characteristics of radar images....6
2.1 Bird echos....6
2.2 Echos of ships and aircraft 7
2.3 Clutter echos....7
2.4 Noise and interference....7
2.5 Filtering using motion information 8

3 Methods of motion analysis....9
3.1 The optical flow method....9
3.2 The Hough transformation 11
3.3 Object matching....13
3.4 Usefulness of the methods....14

4 ALGORITHM for object matching 16
4.1 The score function 16
4.2 Speeding up the algorithm....18
4.3 The pathfinding algorithm....20

5 Conclusions....22

6 Signature 23

Appendix
A Formulae

1 Introduction

1.1 Bird migration

In the lower parts of the airspace, all sorts of bird movements take place. Depending on season and location, these bird movements can either be structured or random. During the bird migration season structure can be recognized in the bird movements. Outside the bird migration seasons the bird movements are mostly random, although there can be structured bird movements between feeding areas and sleeping areas.
In general the bird movements will be a mixture of the movements of several species. Different species may have different flight routes, velocities and directions.

1.2 The ROBIN system

In order to prevent bird strike accidents during training flights of the Royal Netherlands Air Force (RNLAF), the TNO Physics and Electronics Laboratory (TNO-FEL) developed the ROBIN system. ROBIN is an acronym for Radar Observation of Bird INtensity. Currently ROBIN is being used operationally by the RNLAF.
Using a radar image, ROBIN estimates the bird density within a selected region. The estimation is used to decide whether -low altitude- flights are allowed in the selected region. The images that ROBIN uses are obtained by digitizing the video signal of an Air Traffic Control (ATC) radar.
The current ROBIN system operates on a single image or a summation of images. In the case of a single image, the system estimates the areas in which there are unwanted image elements (e.g. clutter). These elements are filtered out of the image, so that only the bird echos remain. The problem is to distinguish between clutter and bird echos. It is not possible to get a perfect separation of clutter and bird echos, so there will be cases where bird echos are missed and cases where clutter is classified as bird echo.
In the case of a summation of images, we can consider the resulting image as a time exposure of the radar screen. Moving birds can be identified by an operator because they are visible as tracks in the summation image.

1.3 Objectives of the project "Motion Analysis of Bird Migration"

The operational ROBIN system uses single or summed radar images. In the case of single images, no information about the movement of the objects in the image can be obtained.
In the case of summed images, moving objects produce tracks of echos in the images. When a summation image is viewed, the information about the motion of the objects is limited by a number of factors :

- There is no information whether an object moves one way or the other.
- Only spatial dependencies and not time-sequential dependencies between objects are visible, which cause 'false tracks' to appear.
- In the case of a higher bird-density, individual echos from one or more images will aggregate.

The objective of the project "Motion Analysis of Bird Migration" is to obtain motion information from a sequence of images and to filter images using that motion information.
An other way of obtaining motion information would be by using a tracking-radar or by using the Doppler information provided by some radars. These possibilities will not be investigated here.

1.4 Digital radar images

ROBIN operates on digital radar image. A *digital* radar image consists of a two dimensional array of picture elements, better known as *pixels*. The value of a pixel is directly proportional to the amplitude of the *analogue* video signal at the corresponding location in the image. Contrary to the analogue case however, only a limited number of values (e.g. 255) are allowed.
If there are more than *two* signal levels in an image, we speak of a *grey value image*. If there are only two possible levels (e.g. 0 and 1) however, we speak of a *binary image*. In binary images, the two possible values of a pixel usually indicate the presence or absence of a certain property at the location of the pixel.

2 Characteristics of radar images

The following elements can be part of a radar image :
- birds or groups of birds
- aircraft and ships
- rain-, sea- and ground clutter
- noise and interference

It should be noted that not all of these elements are necessarily present in one image. In the following paragraphs the properties of the different image elements will be discussed. Subsequently we will discuss the possibilities for using motion information to filter undesirable elements from the images.

2.1 Bird echos

Usually a bird echo in the image will result from a *group* of birds. An *individual* bird can also be detected, depending on distance and size of the bird. A bird echo in the digital image will consist of a spot whose size will vary from a few pixels to a few dozens of pixels, depending on the number and size of the birds. Because a bird moves its wings, its relative reflectivity of radar waves will vary with time[1].
In the case of a group of birds this effect is reduced, provided that there is no correlation between the wing movements of the birds in the group.
In this case there are other effects however. In the first place the group can change its shape during flight. The second effect is that, depending on the wavelength of the radar, interference can occur between the waves reflecting from different birds in the group. Both effects result in a variation in shape and amplitude of the reflection, which can even cause a reflection to disappear from the image.
If the bird density is very high, groups of birds cannot be detected individually. The echos from different groups 'melt' together. The main cause is that the current radar does not provide any information concerning the height of the objects. All objects in the same area but with different heights are imaged on the same location in the image.

[1] L. S. Buurma and B. Bruderer, "*The application of radar for bird strike reduction*", Compilation for the Bird Strike Comittee Europe, The Hague, May 1990

2.2 Echos of ships and aircraft

Since the primary use of the radar that is used for ROBIN, is the detection of aircraft, it is obvious that aircraft and in some cases ships will be visible in the images. These objects disturb the bird density estimation. Therefore it is important that these echos can be removed from the images.
Since aircraft and ships are metal objects, their reflectivity for radar waves is much larger than that of birds. In general aircraft and ships produce strong echos that have a relatively small variation in their appearance and that have a steady course. Aircraft echos move faster than bird echos.

2.3 Clutter echos

2.3.1 Rain clutter

If a rain cloud is dense enough, it can be detected by radar. Generally the dimensions of a cloud echo are much larger than that of a group of birds. A cloud echo can even fill the entire image.
A cloud can consist of a dense area with sharply defined boundaries, but also of large areas of lower density. In that case, it depends on the *local* density whether detection by radar takes place. In the radar image this results in a large area with a speckled texture, which is difficult to distinguish from a concentration of bird echos.

2.3.2 Land clutter

Bird detection takes place in the lower air layers. One of the consequences is that there can be echos in the radar image that result from objects on the ground (trees, towers), especially in the region near the radar.
If an object is tall enough, it will certainly be detected by the radar. Beside that, the atmospheric conditions can influence the propagation of the radar waves in such a way that the waves bend towards the earth surface and reflect from it. This can result in an image filled with echos.
This disruption of the radar image is called land clutter. Since the clutter results from objects on the ground, it will not move in the radar image, although the shape and intensity of the clutter can vary in time, due to the variation in propagation.

2.4 Noise and interference

Noise occurs in the signal chain of the radar. The noise in the image is not correlated in space and time. The ROBIN system uses an active control mechanism that adapts the gain of the system depending on the amount of noise detected in the signal. This causes the number of noise pixels in an image to be approximately constant.

Interference in radar images is often caused by other radars of which the waves interfere with the bird radar or by side-lobes of the bird radar itself.

2.5 Filtering using motion information

2.5.1 Motion information

Besides the fact that motion information on itself can be important for bird density forecasts, it can also be used to distinguish between bird echos and other echos. In this way radar images can be filtered, which results in a better estimation of bird density.

2.5.2 Filtering of rain clutter

In general, rain clouds will have a motion pattern that differs from that of migrating birds. This means that, using motion information, clouds can be distinguished from birds. Motion information can be used as additional criterion next to criteria as size and shape of the echo. It is even possible to use meteorological information in order to distinguish clouds from birds.

2.5.3 Filtering of land clutter

Land clutter can be considered to be standing still. Depending on changing propagation conditions, the amplitude of the clutter can vary with time, but the location of the clutter remains the same. This property can be used in detecting ground clutter. Since we are interested in the motion of birds, it is possible to filter out all the objects that have a velocity lower than the minimum bird velocity, thus removing ground clutter.

2.5.4 Filtering of noise

The noise that occurs in images is not correlated in time and in place. This means that in a sequence of images, the noise pixels will be at different positions in subsequent images. If the noise pixels are considered to be objects, these objects seem to move randomly without any coherence. This fact can be used to distinguish noise from birds, since birds will tend to have a less random motion pattern.

3 Methods of motion analysis

There are three methods of motion analysis that will be compared in this chapter, knowing :

- the optical flow method.
- Hough transformation of summation images.
- object matching.

The specific properties, advantages and disadvantages of the different methods will be discussed. One of the methods will be chosen and will be discussed in further detail in chapter 4.

3.1 The optical flow method

The optical flow method is based on the flow of light intensity. An image is defined as a two-dimensional distribution of light. If we have a sequence of images where motion is present, this can be modelled by assigning a motion vector to each of the pixels in each image. This motion vector indicates where the corresponding pixel will be located in the subsequent image in the sequence. The result of this method consists of an optical flow field (Example in fig 3.1).

3.1.1 Intensity constraint

The optical flow method is based on the conservation of intensity. This means that no intensity is lost in the transition from one image to the other. This requires that :

$$I(x + \Delta x, y + \Delta y, t + \Delta t) = I(x, y, t) \tag{3.1}$$

where x and y are image coordinates and t is time. We call this condition the intensity constraint. If we perform a Taylor expansion of the left term of eq. 3.1, we get :

$$I(x + \Delta x, y + \Delta y, t + \Delta t) =$$

$$I(x, y, t) + \partial I/\partial x \cdot \Delta x + \partial I/\partial y \cdot \Delta y + \partial I/\partial t \cdot \Delta t + \ldots\ldots \tag{3.2}$$

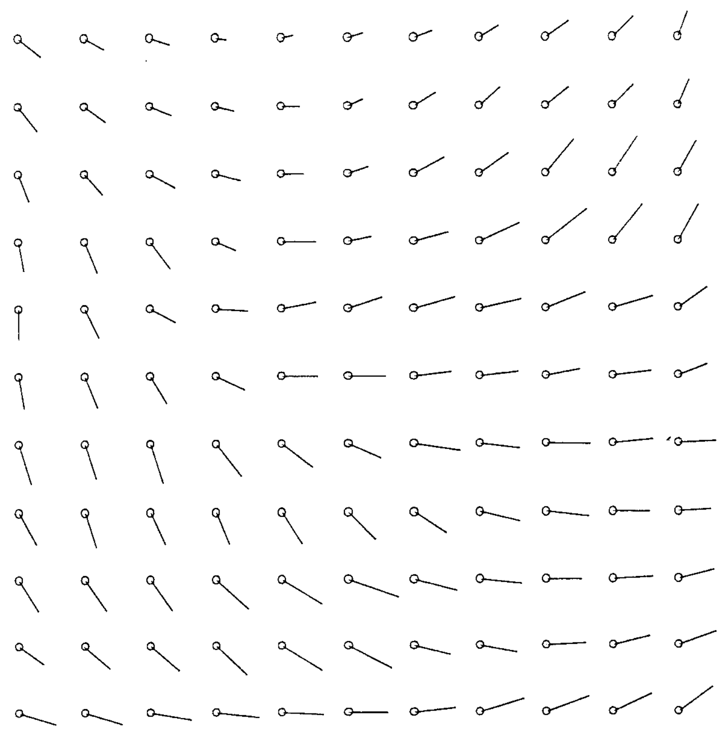


Fig. 3.1: Example of an optical flow field.

From 3.1 and 3.2 we learn that if we let $\Delta t \rightarrow 0$ and neglect high order terms, we can say that :

$$I_x(x, y) \cdot u(x, y) + I_y(x, y) \cdot v(x, y) + I_t(x, y) = 0 \qquad (3.3)$$

where $I_x(x,y)$, $I_y(x,y)$ and $I_t(x,y)$ are the gradients of intensity : $\partial I/\partial x$, $\partial I/\partial y$ and $\partial I/\partial t$ and $u(x,y)$ and $v(x,y)$ are the velocities dx/dt and dy/dt in the point x, y. The three intensity gradients can be determined from the image sequence, while $u(x, y)$ and $v(x, y)$ are the unknowns.
Because of the fact that we have two unknowns and only one equation for each point (x, y), we will need an extra constraint to find a unique solution.
A possible extra constraint is the *smoothness constraint.* This constraint corresponds to the assumption that the optical flow has a smooth behaviour and that neighbouring pixels have similar motion vectors.

3.1.2 Calculating the optical flow field

Finding the optical flow field involves the minimization of a functional that depends on the intensity constraint and the smoothness constraint. We must minimize this functional with respect to the unknowns u and v. For our type of images (radar image of birds, 10 sec between images) it is very hard to determine the gradients of intensity in (3.3) because the movement of a birdspot is several pixels in subsequent images, and the intensity of the spot is not constant.

3.2 The Hough transformation

3.2.1 Applicability of the Hough transform

The Hough transform can be used on summation images and on lists of (x, y) coordinates that give the positions of (centres of gravity of) objects. ROBIN has the ability to create an image that is the summation of a given sequence of images. Birds that are in motion, will show up as dotted tracks in the summation image. For a human being it is not hard to recognise these tracks, even if the dots are somewhat apart. This fact is used in the current method of performing bird counts, where a time exposure taken from the radar screen is interpreted by an operator. To achieve track recognition by the computer, we need to have some sort of structuring transformation that can be applied to an image. The Hough transformation is such a transformation. This transformation registers how many points in a summation image or in an (x, y) list satisfy a certain equation. If this equation represents a line, it can therefore be used to count the number of points that are on the same line. If this number exceeds a certain threshold, there is enough 'evidence' that there is a bird-track present.

3.2.2 The principle of the Hough transformation

The Hough transform transforms an image to a parameter space. To describe a line, we can choose from different representations. One of these representations is the normal equation : $y = ax + b$. Here a and b are the parameters of the line. This representation however has one disadvantage : a line parallel to the y - axis cannot be represented.

A more suitable representation therefore would be : $x \cos\theta + y \sin\theta = \rho$. The meaning of θ and ρ are illustrated in fig. 3.2. The Hough transform creates a parameter space where ρ and θ are the parameters. A straight line in normal space corresponds with one single point (ρ, θ) in the parameter space.

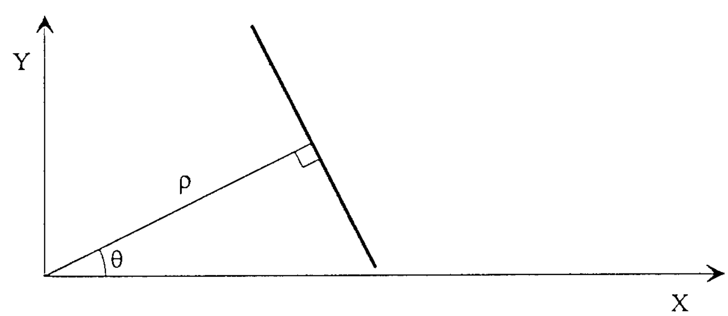


Fig. 3.2: Parameters ρ and θ of a line in the x, y-plane.

For every combination of ρ and θ there is one unique line in the original image. A single point (x_p, y_p) in the original image can be considered to be part of an infinite number of lines, since for every value of ρ a value of θ can be found for

which $x_p \cos\theta + y_p \sin\theta = \rho$ is satisfied. This means that a single point in the original image transforms into a sinusoid in the Hough space.
Now suppose there are a number of points in the original image that are on the line given by : $x \cos\theta_l + y \sin\theta_l = \rho_l$. Each of these points produces a sinusoid in the Hough space (fig 3.3). All these sinusoids intersect in the point (ρ_l, θ_l). By selecting the points in the Hough space where the most sinusoids intersect, the lines on which the most points are situated are selected in the original image.
The implementation of the Hough transformation can be divided into the following steps:

- For every nonzero pixel in the summation image or for every (x, y) pair in the coordinate lists, calculate the sinusoid in the HOUGH space.
- For every point (ρ, θ) in the Hough space, calculate how many sinusoids intersect in the point.
- Take only the points that are a local maximum in the Hough space.
- Generate the lines that correspond to the points (ρ_i, θ_i) that have remained.

An example of the use of the Hough transform is illustrated in fig. 3.3.

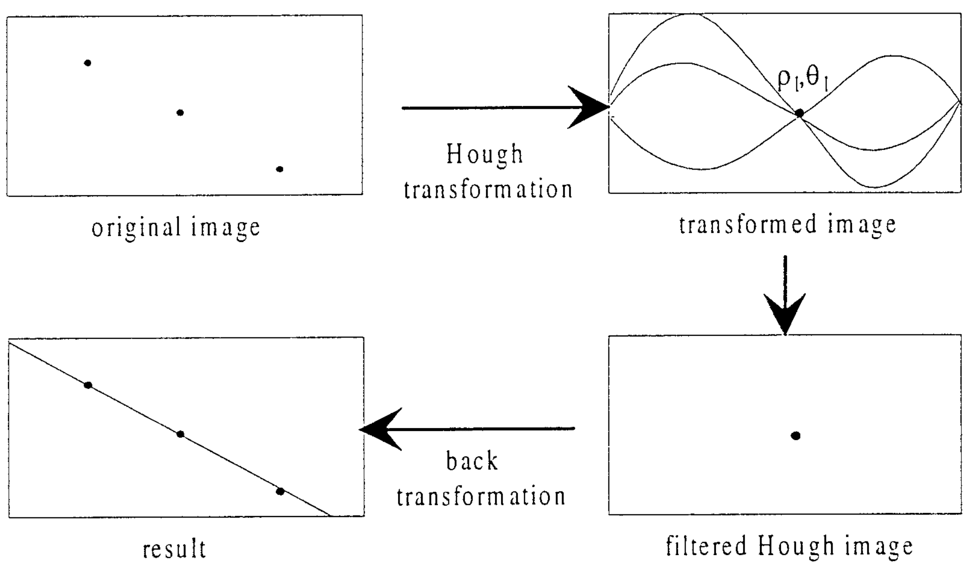


Fig. 3.3: Example of the use of the Hough transform.

The result of the Hough transformation is a set of lines on which at least a certain number of points are situated.

3.3 Object matching

3.3.1 Preprocessing of images

The method is based on the assumption that an image is composed of a number of distinguishable objects and that there is a certain amount of similarity between the objects (in subsequent images) that result from the same source.
It is necessary to perform some preprocessing that isolates the objects and that measures a number of parameters that are characteristic for the objects.

3.3.2 Matching process

Any sequence of objects, obtained from different images in the right order of time, forms a potential bird trajectory or path. To each path a score can be assigned, expressing how well the objects in the path fit together. The combination of paths with the best overall score is the result of the matching process.
It is possible that there are objects that do not belong to any path or on the other hand that a path misses one or more of its objects.

3.3.3 Parameters for score evaluation

There are a number of parameters that are suitable to be used in the calculation of the score.

a) The position of (the centre of gravity of) an object: the movement within a certain time-interval is limited.
b) The velocity and direction of an object, generally these will vary relatively little in a short period of time.
c) The strength of the signal of the object. Although fluctuations will occur, there will be some correlation in time.
d) The number of objects that are part of a path (referred to as the length of the path). If many objects in a path are absent, the path will be less probable.
e) Collectivity of motion. The individual (groups of) birds of the same species usually travel in the same direction at the same speed.

3.3.4 Optimization

The method where the overall score is optimized as function of all the possible combinations of paths, as described in par. 3.3.2, will need a large amount of calculations. This is caused by the large number of possible paths and the even larger number of combinations of paths.
If however we are willing to accept a sub-optimal solution to the optimalization problem, it may be possible to reduce the amount of processing required significantly.

3.4 Usefulness of the methods

3.4.1 The optical flow method

If the optical flow method, using the smoothness constraint, is applied to a sequence of images, the result consists of a two-dimensional velocity vector field. Within this vector field, direction and amplitude of neighbouring vectors are similar. There are no discontinuities in the field. One of the consequences is that it is not possible that velocity vectors cross each other.
The main disadvantage of this method becomes clear if we consider the fact that it is possible that there are birds with different directions of flight in one radar image (see par 1.1). The optical flow method cannot model this situation, because of the nature of its result as described in the above paragraph. Therefore the optical flow method is inadequate for motion analysis on bird images.

3.4.2 The Hough transformation

The result of a Hough transformation consists of a set of parameters of lines on which a certain number of points lie. The transformation does not provide any information about the exact location of the points on the line however. This means that if the set of parameters is used to project lines onto the original image, it is hard to say where the lines start and end.
There will be post-processing involved in finding out what parts of a line should remain and what parts can be discarded. If it is impossible to do so, the image will fill up with lines, which does not provide any information. Beside that, no information can be provided about the amplitude of the velocity, only the direction can be found.
The main disadvantage of this method is the behaviour at high bird densities. In that case, it is very likely to find a number of points that look as if they lie on a straight line, even if no such dependency exists. It has become impossible to distinguish between real lines and lines resulting from points that form lines randomly. This effect occurs because no time-dependency is used in this method.

3.4.3 Object matching

The possibility of using a combination of the parameters described in par. 3.3.2 for the score function is very attractive, furthermore paths do not have to be limited to straight lines. Crossing paths are no problem and the time-dependency is incorporated in the score by means of position and velocity. The method offers possibilities to create a continuous tracking process using partially overlapping subsequent time-intervals. To limit the processing time required, a number of 'tricks' will be needed.

3.4.4 Preliminary conclusion

The optical flow method is not suitable in the case of superimposed migration of several species having different velocities and flight directions. The Hough transform ignores the coherence in time and position of consecutive echoes and does not discriminate between individual tracks. Object matching has none of these disadvantages and merges several types of information.
Therefore object matching is regarded as the most promising method for motion analysis of bird images. This method is chosen for further investigation.

4 ALGORITHM for object matching

4.1 The score function

4.1.1 Requirements for the score function

The score function determines the results of the matching process. The score is some kind of measure for the probability that a path formed by a sequence of objects is a real bird trajectory. The score is only used in comparisons between paths and does not need to have any physical or statistical meaning.
Because the score function has to be evaluated many times, the function must not be very complicated. Preferably it should be possible to use partial results of a path for the score calculation of an extended path. The different criteria should be easy to combine, for example as a weighed sum.

4.1.2 Description of the score function

The model for a bird trajectory is a straight line with constant speed and identical echos along the track; the speed, flight direction and echo strenght have disturbances which are assumed to have a random character with a Gaussian distribution.
The formula:

$$\sum_{i=1}^{n}\left(\frac{x_i-\mu_i}{\sigma_i}\right)^2$$

could be used as the score function, where

x_i	is any of speed, direction or strength of the objects
μ_i and σ_i	are the corresponding mean values and deviations
n	is the total number of parameters for all objects.

Parameters which are incomparable in nature are transformed to indentical quantities. Greater differences between x_i and μ_i lead to a lower score. However, longer sequences of objects will also lead to a lower score even if the differences x_i - μ_i are small.
The solution to this can be found when the random character of the x_i is considered.

Let x_i, i = 1..n be independent random variables with Gaussian distribution. Then the formula

$$X^2=\sum_{i=1}^{n}\left(\frac{x_i-\mu_i}{\sigma_i}\right)^2$$

is also random following the chi-square distribution with n degrees of freedom. The probability that X^2 is less than a certain value χ^2 is given by the function $P(\chi^2, n)$. In the reverse case

$\chi^2(n, P)$ is the value for which P is the probability that $\chi^2 - X^2$ is greater than zero.
If P is chosen to be constant then

$$\chi^2(n,P) - \sum_{i=1}^{n}\left(\frac{x_i - \mu_i}{\sigma_i}\right)^2$$

is a comparable quantity for different values of n.
Some values of $\chi^2(n, P)$ are listed in table 4.1.

Table 4.1: χ^2 versus P and n.

P =	0.100	0.500	0.900
n = 1	0.016	0.455	2.706
2	0.211	1.386	4.605
3	0.584	2.366	6.251
5	1.610	4.351	9.236
7	2.833	6.346	12.017
10	4.865	9.342	15.987
15	8.547	14.339	22.307
20	12.443	19.337	28.412
30	20.599	29.336	40.256

Since the expectation value of X^2 is n, the choice of P can be used to adjust the balance between the lenght of a sequence and deviations from uniform movement. Unfortunately, the values for μ_i en σ_i are not known and the speed and the flight direction are not easily obtained from the positions in polar or rectangular coordinates.
A guess for σ_i can be made by observing bird motion when the bird density is low and the tracks can not be confused.
The μ_i are estimated from the object data of the current path for which the score has to be calculated; the effect is that the degrees of freedom have to be reduced. Finally the score function is rewritten in terms of the rectangular velocity components instead of speed and direction.
The formula for the score function after these manipulations is:(See Appendix)

$$\text{score} = \chi^2(3k-2,P) - \frac{\sum_{i=1}^{k}(Vx_i^2 + Vy_i^2) - \frac{(\sum_{i=1}^{k} Vx_i)^2 + (\sum_{i=1}^{k} Vy_i)^2}{k}}{c_t} - \frac{\frac{k.\sum_{i=1}^{k}(Vx_i^2 + Vy_i^2)^2}{\sum_{i=1}^{k}(Vx_i^2 + Vy_i^2)} - \sum_{i=1}^{k}(Vx_i^2 + Vy_i^2)}{c_r} - \frac{\frac{(k+1).\sum_{i=0}^{k} m_i^2}{\sum_{i=0}^{k} m_i} - \sum_{i=0}^{k} m_i}{c_m}$$

This function is easy to calculate; if the search over all paths is organised as depth-first search tree, the partial sums may be stored in a stack and reused for all possible extended paths. The values of χ^2 are calculated once and stored in an array (depending on k).

4.2 Speeding up the algorithm

4.2.1 Sub-optimal solution

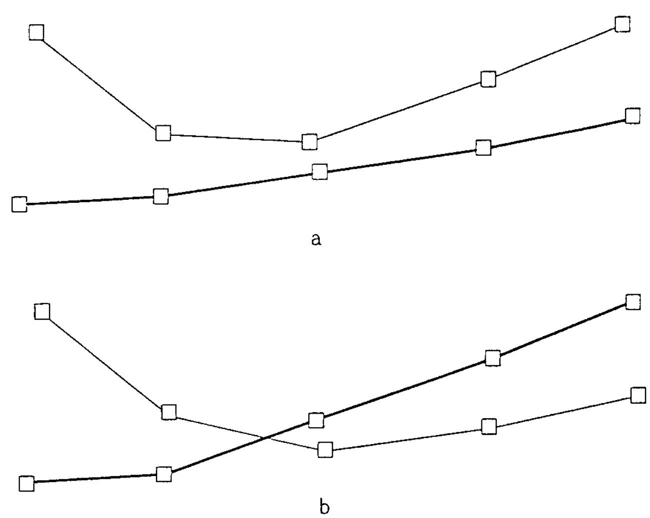


Fig 4.1: Non unique solution.

Optimization over all combinations of paths is a very costly computation, because of the combinatorial explosion. If the paths are sufficiently far apart, not all possibilities have to be considered and local optimization is possible.
In the extreme case, optimization can be performed path-wise. To satisfy the condition that an object can only be part of one path, it is necessary to choose only the best path and repeat the procedure for all remaining objects until no more candidates remain. Fig 4.1 illustrates that this approach does not always lead to the best solution.
In case (a) of fig. 4.1 the bold line has the highest score of all possibilities and the line is composed of the remaining objects, yielding a very low score.
Case (b) of fig. 4.1 shows two solutions each with a score lower than the best of case (a) but the sum of the scores may be higher then in case (a).

4.2.2 Reducing the number of potential paths

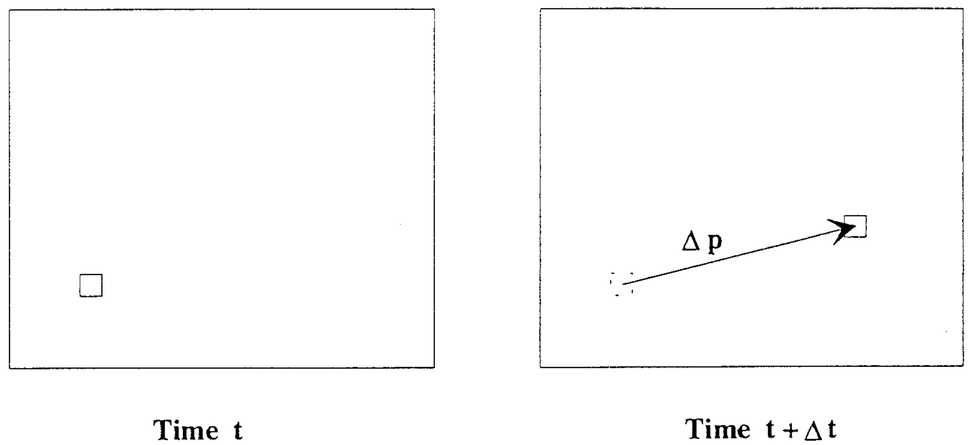


Fig 4.2: The definition of Δp/Δt.

Instead of using the entity Δp/Δt (as depicted in fig 4.2) in the score function for all possible paths, only those pathsegments[2] are considered for which Δp/Δt is within certain limits. A side effect is that objects that are very fast or very slow can end up in the wrong paths.
This mechanism may also be used to exclude certain speed/direction combinations (rain clutter removal) or to select a speed/direction region in the case of a strong collective motion.

4.2.3 Using sub-sequences of images

In the case of longer sequences of images, the number of potential paths grows roughly with [the number of objects per image] to the power [the number of images], even if the restrictions of paragraph 4.2.2 are applied.
A shorter sequence of images is better for the processing time, but finding the correct matches becomes more difficult because of the limited amount of information. By applying repeated operations on (overlapping) partial sequences, the processing time for long sequences can be diminished. In this case the last segments of the paths found in a previous stage are used as 'seeds' for paths in the new images. Also new starting points for paths are generated.

4.2.4 Reducing the time interval

With increasing time interval between two images, the number of candidate objects for a path increases (par 4.2.2). On average, the number is proportional to the square of the time interval. The radar determines the minimum length of the time interval, which equals the minimum time required for the antenna to complete

---

2 A pathsegment is defined as the connection between two objects in two successive images.

one rotation. Because objects can disappear from an image due to effects described in par. 2.1, it is necessary to use several rotations to be able to bridge the gap in the path caused by the absence of an object.
Reducing the number of time intervals between pairs of images, will speed up the matching process, but it will cause some paths to split up or to disappear entirely.

4.2.5 Pruning of the search tree

In the score function, the score of a path is increased when there is large stability in the velocity vector. If large changes in the velocity vector occur in a path, score calculation can be omitted and all extended paths do not have to be evaluated. Not all bird motions are equally regular, those paths associated with less regular bird motions cannot always be found.

4.2.6 Optimizing the datamodel

A path can be regarded as a sequence of objects or as a sequence of object pairs. In the latter case many intermediate values (such as $Vx_i^2 + Vy_i^2$) may be calculated once and used many times. The consequence is that a large amount of data has to be stored.

4.3 The pathfinding algorithm

4.3.1 Preprocessing

For every image in the sequence a *detection list* is generated. A detection list consists of one record for each object in the image, storing the location of the object (centre of gravity), the size (number of pixels) and mass (sum of the pixel intensities) of the object.

4.3.2 Initialisation

From the detection lists a tree is built. An object is connected to every other object in later images for wich the path segment satisfies certain conditions. So there are also segments that skip a number of images.
Paths that already (partially) exist are treated in a different way, each object is only linked to the segment that is actually part of the path. The starting point of this path is connected to objects in earlier images, the endpoint of this path can be the starting point of a path segment.

4.3.3 Pathfinding

The segments are accessed in the order of a depth-first tree. If a node is reached where no more acceptable continuations can be found, the search continues at the previous level. For every candidate extension of the path the score is calculated from the current path and its extension.
For every segment the new score is compared to its previous best score. If the new score is better, the score of every segment of the path is replaced by the new score

and a link to the next segment in the path is stored. The first and last path segments are marked.

4.3.4 The administration of paths

Paths that have a constant score from start to end mark are put in a list, the *found-list*. Objects that are part of a path in the *found-list* cannot be part of any other path, therefore these objects and all segments that start from or end at these objects must be removed from the tree of path segments. Also objects that are not part of any path (loose objects) are removed, becaused in the next cycle they will again turn up as loose objects. All remaining segments in the tree are cleared and a new cycle begins. This repeats until there are no more objects available.

5 Conclusions

The algorithm is easily adapted for more object feature parameters or 3 dimensional data.
The algorithm can be run in parallel on:

- sub sequences of images;
- partial images;
- different speed and/or direction regions.

One extra run must be made on the whole sequence of complete images to correct for border effects (using the partial results).
The algorithm can be used iteratively in the same way as in parallel execution, a special case is the incremental use for continuous tracking.

An implementation of the algorithm has been made containing all optimizations as mentioned in 4.2 and iteration over speed/direction regions. These regions are based on a cluster analysis of all possible velocity vectors of the remaining objects and selected in a decreasing order of bird motion magnitude in the regions.
This implementation is in operational use in the Royal Netherlands Airforce at the moment.
The results of this implementation in a clutter free situation agree well with the visual impression of a motion picture of the images. Only a few percents of the tracks are wrong or not found in images with medium bird density. At high density, where the nearest neighbour distance is less than the distance travelled in the time between two images, the eye is not able to identify individual tracks, only a global impression of motion exists. In this case no comparison can be made if no other means of finding the true tracks are available.
If clutter is present it is excluded, based on statitics in time and space. Speckled moving rain regions are not completely removed and the algorithm finds spurious tracks on the edges.
It is recommended to do some more research to avoid these tracks either by improvement of the clutter filters and bird detection or by postprocessing of the tracks found.

6 Signature

Dr. H.E. Keus
Groupleader Operational Systems

M.W. Ockeloen
Author/project manager

Appendix A Formulae

The score in [4.1.2] is written as:

$$\chi^2(n,P) - \sum_{i=1}^{n} \left(\frac{x_i - \mu_i}{\sigma_i}\right)^2$$

Suppose we have k+1 objects, numbered 0..k. Because velocity is calculated from the object positions, there are k velocity vectors each having 2 degrees of freedom. Furthermore there are k+1 object masses (see 4.3.1) each with 1 degree of freedom.
The score function in some more detail is:

$$\chi^2(3k+1,P) - \sum_{i=1}^{k} \left(\frac{V_i - \mu_v}{\sigma_v}\right)^2 - \sum_{i=1}^{k} \left(\frac{h_i - \mu_h}{\sigma_h}\right)^2 - \sum_{i=0}^{k} \left(\frac{m_i - \mu_m}{\sigma_m}\right)^2 \qquad (1)$$

where V refers to speed, h to direction and m to mass.

If the variation in direction is relatively small then

$$\left(\frac{V_i - \mu_v}{\sigma_v}\right)^2 + \left(\frac{h_i - \mu_h}{\sigma_h}\right)^2$$

can be approximated by:

$$\left(\frac{Vr_i - \mu_r}{\sigma_r}\right)^2 + \left(\frac{Vt_i - \mu_t}{\sigma_t}\right)^2 \qquad (2)$$

where Vr is the velocity component in the long term flight direction and Vt the component perpendicular to Vr.

Equation (2) is rewritten as:

$$\sum \frac{(Vt_i - \mu_t)^2 + (Vr_i - \mu_r)^2}{\sigma_t^2} + \sum (Vr_i - \mu_r)^2 . \left(\frac{1}{\sigma_r^2} - \frac{1}{\sigma_t^2}\right) \qquad (3)$$

The function

$$(Vt_i - \mu_t)^2 + (Vr_i - \mu_r)^2$$

equals

$$(Vx_i - \mu_x)^2 + (Vy_i - \mu_y)^2$$

where Vx_i and Vy_i are the velocity components in the x, y coordinate grid.

The last term in (3) contains a factor

$$\sum\left(\frac{Vr_i - \mu_r}{\sigma_r}\right)^2 \tag{4}$$

If $\sigma_r << \mu_r$ and the distribution of Vr_i^2 is approximatily a Gaussion distribution with mean μ_r^2 and deviation $2\mu_r\sigma_r$, the factor (4) is equivalent to

$$\sum\left(\frac{Vr_i^2 - \mu_r^2}{2\mu_r\sigma_r}\right)^2$$

where Vr_i^2 equals $Vx_i^2 + Vy_i^2$.

Combining these results, the score function becomes:

$$\chi^2(3k+1,P) - \frac{\sum(Vx_i - \mu_x)^2 + (Vy_i - \mu_y)^2}{\sigma_t^2} - \frac{\sum(Vx_i^2 + Vy_i^2 - \mu_r^2)}{4\mu_r^2\sigma_r^2\left(\frac{\sigma_t^2}{\sigma_t^2 - \sigma_r^2}\right)} - \sum\left(\frac{m_i - \mu_m}{\sigma_m}\right)^2 \tag{5}$$

The values of μ_t, μ_r and μ_m are in general not known beforehand so they must be estimated from the data.

If there are n data values x_i then μ is replaced by

$$\sum_{i=1}^{n} \frac{x_i}{n}$$

denoted by <x>, so

$$\sum_{i=1}^{n}(x_i - <x>)^2 = \sum_{i=1}^{n}(x_i^2 - 2x_i <x> + <x>^2) =$$

$$\sum_{i=1}^{n} x_i^2 - n<x>^2 = \sum_{i=1}^{n} x_i^2 - \frac{(\sum_{i=1}^{n} x_i)^2}{n} \tag{6}$$

While <x> depends on x_i one degree of freedom is lost. This is clearly demonstrated by n = 1; formula (6) yields 0 in that case.

In formula (5) three independent quantities are present, the total degrees of freedom must therefore be reduced by 3.

Substitution of (6) in (5) and the assumption that $\sigma_m{}^2 = \sigma_{m1} \cdot \mu_m$ yields:

$$\text{score} = \chi^2(3k-2,P) - \frac{\sum_{i=1}^{k}(Vx_i{}^2 + Vy_i{}^2) - \frac{(\sum_{i=1}^{k} Vx_i)^2 + (\sum_{i=1}^{k} Vy_i)^2}{k}}{c_t}$$

$$- \frac{\frac{k.\sum_{i=1}^{k}(Vx_i{}^2 + Vy_i{}^2)^2}{\sum_{i=1}^{k}(Vx_i{}^2 + Vy_i{}^2)} - \sum_{i=1}^{k}(Vx_i{}^2 + Vy_i{}^2)}{c_r} - \frac{\frac{(k+1).\sum_{i=0}^{k} m_i{}^2}{\sum_{i=0}^{k} m_i} - \sum_{i=0}^{k} m_i}{c_m}$$

where: $c_t = \sigma_t{}^2$, $c_r = 4\sigma_r{}^2.(\frac{\sigma_t{}^2}{\sigma_t{}^2 - \sigma_r{}^2})$ and $c_m = \sigma_{m1}$

(7)

A minimum number of three objects in a path is necessary to calculate (7). The assumption of $\sigma_m{}^2 = \sigma_{m1} \cdot \mu_m$ is based on the physical properties of radar reflection. This and the Gaussian distribution of m_i are crude approximations.

REPORT DOCUMENTATION PAGE
(MOD-NL)

1. DEFENCE REPORT NO. (MOD-NL)	2. RECIPIENT'S ACCESSION NO.	3. PERFORMING ORGANIZATION REPORT NO.
TD95-0019		FEL-94-A177
4. PROJECT/TASK/WORK UNIT NO.	**5. CONTRACT NO.**	**6. REPORT DATE**
22254	A90KLu670	April 1996
7. NUMBER OF PAGES	**8. NUMBER OF REFERENCES**	**9. TYPE OF REPORT AND DATES COVERED**
26 (incl. 1 appendix, excl. RDP & distribution list)	-	

10. TITLE AND SUBTITLE

Motion Analysis of bird migration

11. AUTHOR(S)

M.W. Ockeloen, J. Nobel

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Physics and Electronics Laboratory, P.O. Box 96864, 2509 JG The Hague, The Netherlands
Oude Waalsdorperweg 63, The Hague, The Netherlands

13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES)

Royal Netherlands Airforce
DMKLu, Postbus 20703, 2500 ES The Hague, The Netherlands

14. SUPPLEMENTARY NOTES

The classification designation Ongerubriceerd is equivalent to Unclassified, Stg. Confidentieel is equivalent to Confidential and Stg. Geheim is equivalent to Secret.

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

To reduce the in-flight bird strike risk, the TNO/FEL laboratory developed the ROBIN system for the RNLAF. The ROBIN system uses singular or summed radar images. Because motion of objects in the radar image provides much information about the nature of the object, motion analysis is an important feature to improve the filtering of radar images. For this reason the project "Motion Analysis of Bird Migration" was started as a continuation of the ROBIN project.
In this report the advantages and disadvantages of different methods of motion analysis are compared. On the basis of experimental results and theoretical aspects, a choice is made for the method of object matching. The principle and implementation of this method is discussed.

16. DESCRIPTORS	IDENTIFIERS
Bird Collisions	Birdmigration ROBIN Motion Analysis Image Processing

17a. SECURITY CLASSIFICATION (OF REPORT)	17b. SECURITY CLASSIFICATION (OF PAGE)	17c. SECURITY CLASSIFICATION (OF ABSTRACT)
Ongerubriceerd	Ongerubriceerd	Ongerubriceerd
18. DISTRIBUTION AVAILABILITY STATEMENT		**17d. SECURITY CLASSIFICATION (OF TITLES)**
Unlimited Distribution		Ongerubriceerd

Distributielijst

1.	Bureau TNO Defensieonderzoek
2.	Directeur Wetenschappelijk Onderzoek en Ontwikkeling*)
3.	HWO-KL*)
4.	HWO-KLu
5.	HWO-KM*)
6.	HWO-CO*)
7 t/m 9.	KMA, Bibliotheek
10 t/m 13.	DMKLu, t.a.v. Drs. L.S. Buurma
14.	DMKLu, t.a.v. Ing. G. Koeman
15.	Directie TNO-FEL, t.a.v. Dr. J.W. Maas
16.	Directie TNO-FEL, t.a.v. Ir. J.A. Vogel, daarna reserve
17.	Archief TNO-FEL, in bruikleen aan Dr. H.E. Keus
18.	Archief TNO-FEL, in bruikleen aan Drs. M.W. Ockeloen
19.	Archief TNO-FEL, in bruikleen aan Ir. W. Treurniet
20.	Documentatie TNO-FEL
21.	Reserve
	TNO-PML, Bibliotheek**)
	TNO-TM, Bibliotheek**)
	TNO-FEL, Bibliotheek**)

Indien binnen de krijgsmacht extra exemplaren van dit rapport worden gewenst door personen of instanties die niet op de verzendlijst voorkomen, dan dienen deze aangevraagd te worden bij het betreffende Hoofd Wetenschappelijk Onderzoek of, indien het een K-opdracht betreft, bij de Directeur Wetenschappelijk Onderzoek en Ontwikkeling.

*) Beperkt rapport (titelblad, managementuittreksel, RDP en distributielijst).
**) RDP.